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EFFECTS OF BURN RATE ON THE SPATIAL EXTENT OF FRACTURE DAMAGE IN AN UNDERGROUND EXPLOSION (POSTPRINT)

Annual Report 4

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14. ABSTRACT

The quasistatic micromechanical damage mechanics originally formulated by Ashby and Sammis has been made fully dynamical by the incorporation of physically motivated crack growth laws. This rate-dependent damage mechanics has been implemented in the ABAQUS dynamic finite element code and tested by simulating strength data for marble measured over a ten order of magnitude range of loading rates. The model is used here to explore the effect of burn rate (loading rate) on the spatial extent of fracture damage (and hence the elastic radius) and on the S waves generated by an underground explosion. The recent observation by that explosives with low burn rates produce more shear wave radiation than do those with high burn rates can be explained by dynamic fracture effects, and may not be due to gas wedging as originally hypothesized.

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EFFECTS OF BURN RATE ON THE SPATIAL EXTENT OF FRACTURE DAMAGE IN AN UNDERGROUND EXPLOSION

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Sponsored by the Air Force Research Laboratory

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ABSTRACT

The quasistatic micromechanical damage mechanics originally formulated by Ashby and Sammis (1990) has been made fully dynamical by the incorporation of physically motivated crack growth laws. This rate-dependent damage mechanics has been implemented in the ABAQUS dynamic finite element code and tested by simulating strength data for marble measured over a ten order of magnitude range of loading rates. The model is used here to explore the effect of burn rate (loading rate) on the spatial extent of fracture damage (and hence the elastic radius) and on the S waves generated by an underground explosion. We find that the recent observation by Weston Geophysical and New England Research that explosives with low burn rates produce more shear wave radiation than do those with high burn rates can be explained by dynamic fracture effects, and may not be due to gas wedging as originally hypothesized.

OBJECTIVES

In this paper we use our recently developed dynamic damage mechanics to simulate explosions in brittle rock. The primary objective is to explore the effect of "burn-rate" (loading rate) on the generation of fracture damage and associated shear waves in the non-linear source regime. Our motivation is the recent field observation by Weston Geophysical and New England Research that explosives with a lower burn-rate produce more S wave radiation than equivalent explosives with a higher burn-rate. Our explanation in terms of dynamic fracture mechanics offers an alternative to the more common explanation in terms of the explosive gasses.

RESEARCH ACCOMPLISHED

We have formulated a fully dynamical version of the Ashby and Sammis (1990) micromechanical damage mechanics that incorporates the physics of crack propagation at high loading rates. This dynamic damage mechanics has been incorporated as a user-defined subroutine in the commercial ABAQUS dynamic finite element code. Details of the new damage mechanics and a test using high loading-rate experiments in marble are in press as contribution to a special volume of the Journal of Applied Mechanics in honor of James Rice to be published in January 2012. Rather than repeat the details here, we summarize the key results and go on to investigate the role of burn-rate in the spatial extent of fracture damage and the generation of S waves.

Extending Micromechanical Damage Mechanics to High Loading Rates

The micromechanical damage mechanic formulated by Ashby and Sammis (1990) and used by Johnson and Sammis (2001) to calculate the fracture damage surrounding the 1993 NPE explosion (and the associated P and S wave secondary seismic radiation) is a quasistatic theory. It assumes elastic equilibrium when calculating the stress intensity factor at nucleating and growing fractures, and it assumes that the cracks grow until this stress intensity falls to it steady state critical value. However, loading rates in the non-linear source region of explosions (as well meteorite impacts and near the rupture tip of earthquakes) are so high that these quasistatic assumptions break down. Deshpande and Evans (2008) introduced an ad hoc crack growth law into the Ashby/Sammis damage mechanics to accommodate for dynamic crack growth under non-equilibrium loading conditions. They used this formulation to investigate the performance of ceramic armor plating under impact loading. We have replaced their arbitrary crack growth law with one based on the following theoretical and experimental considerations.

For a stationary finite crack under transient loading conditions the dynamic stress intensity factor, K_I^d evolves with time following the application of loads. As illustrated in Figure 1, it rises sharply with time, overshoots the equivalent static value K_{st} by a considerable amount, and then oscillates around the static value with decreasing amplitude. This oscillation is due to the Rayleigh waves traveling back and forth along the surface of the crack with decreasing intensity.

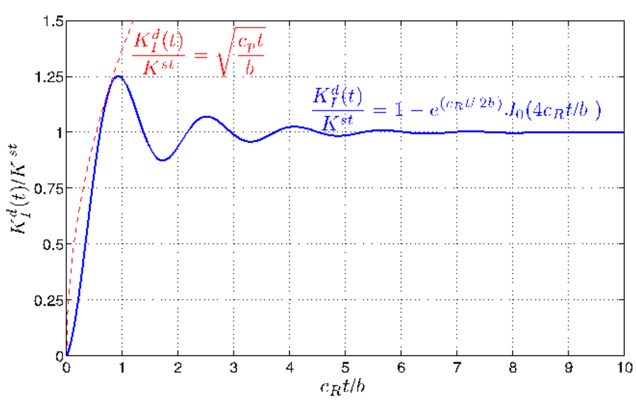

Figure 1 Temporal evolution of the dynamic stress intensity factor, scaled by its static limit. $c_R t/b$ denotes the time from the beginning of loading to the instant at which fracture initiation occurs scaled by the Rayleigh wave speed c_R and the crack half-length b.

As a material parameter, K_{IC} can only be obtained through experimental measurements and is found to vary with loading rate. Figure 2a shows the critical value of the stress intensity factor K_I for crack nucleation as a function of loading rate while Figure 2b shows the critical value of K_I for crack propagation as a function of propagation velocity *v*.

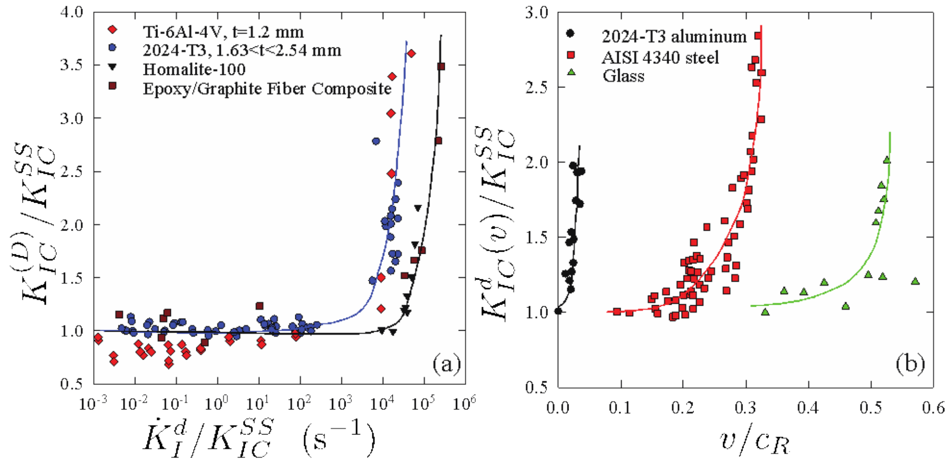

Figure 2. (a) Normalized dynamic $K_{IC}^{(D)}$ for fracture initiation as a function of loading rate for several materials. (b) Normalized K_{IC}^{d} for fracture propagation as a function of crack-tip velocity for various materials.

An expression that represents the dynamic behavior in Figures 1, 2 and Freund`s (1973) result on the dynamic stress intensity factor of a growing crack have been incorporated into a user developed material subroutine (VUMAT) in ABAQUS to replace the ad-hoc growth law currently used by Deshpande and Evans (2008).

Experimental Validation of Dynamic Damage Mechanics

Figure 3 shows the failure strength σ_p as a function of loading strain rate $d\varepsilon/dt$ in Dionysus-Pentelicon marble (from the Parthenon). The data are unpublished results of uniaxial and Hopkinson split bar experiments that are presented in our paper (Bhat et al., 2011).

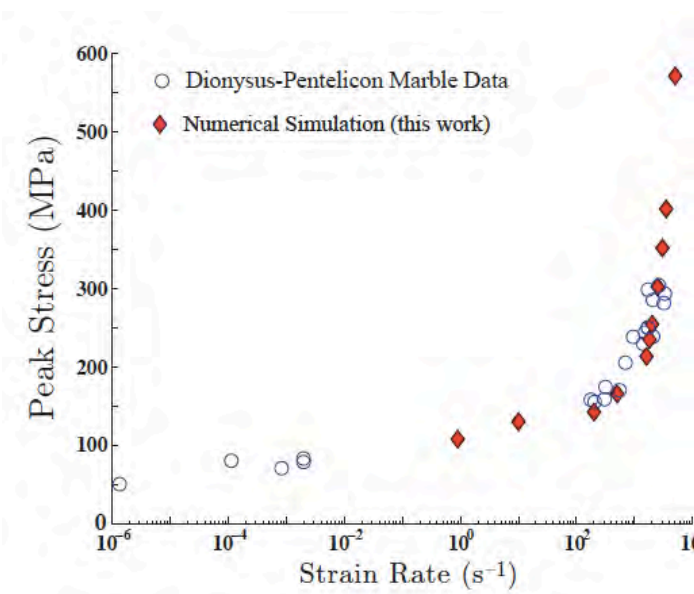

Figure 3. Comparison between experimental measurements of the strength of Pentelicon marble as a funtion of loading rate and the predictions of our dynamic damage mechanics model (Bhat, et al., 2011, in press)

This result shows the power of our micromechanical model. Only two model parameters are required (the inital crack density *Do* and flaw size *a*), which were determined from the quasistatic uniaxial data at low strain rates near 10^{-6} s^{-1}. The diamonds are the model predictions at high loading rates, which clearly capture the sudden increase in strength at very high loading rates (as are typical in the non-linear source region of underground nuclear explosions).

Dynamic Fracture Damage in the Source Region of an Explosion: The Effect of Burn-Rate

Figures 4 and 5 below show the effect of the rise time and the duration of pressure pulses applied to the surface of a 1 m diameter cavity in a rock with initial damage Do = 0.1.

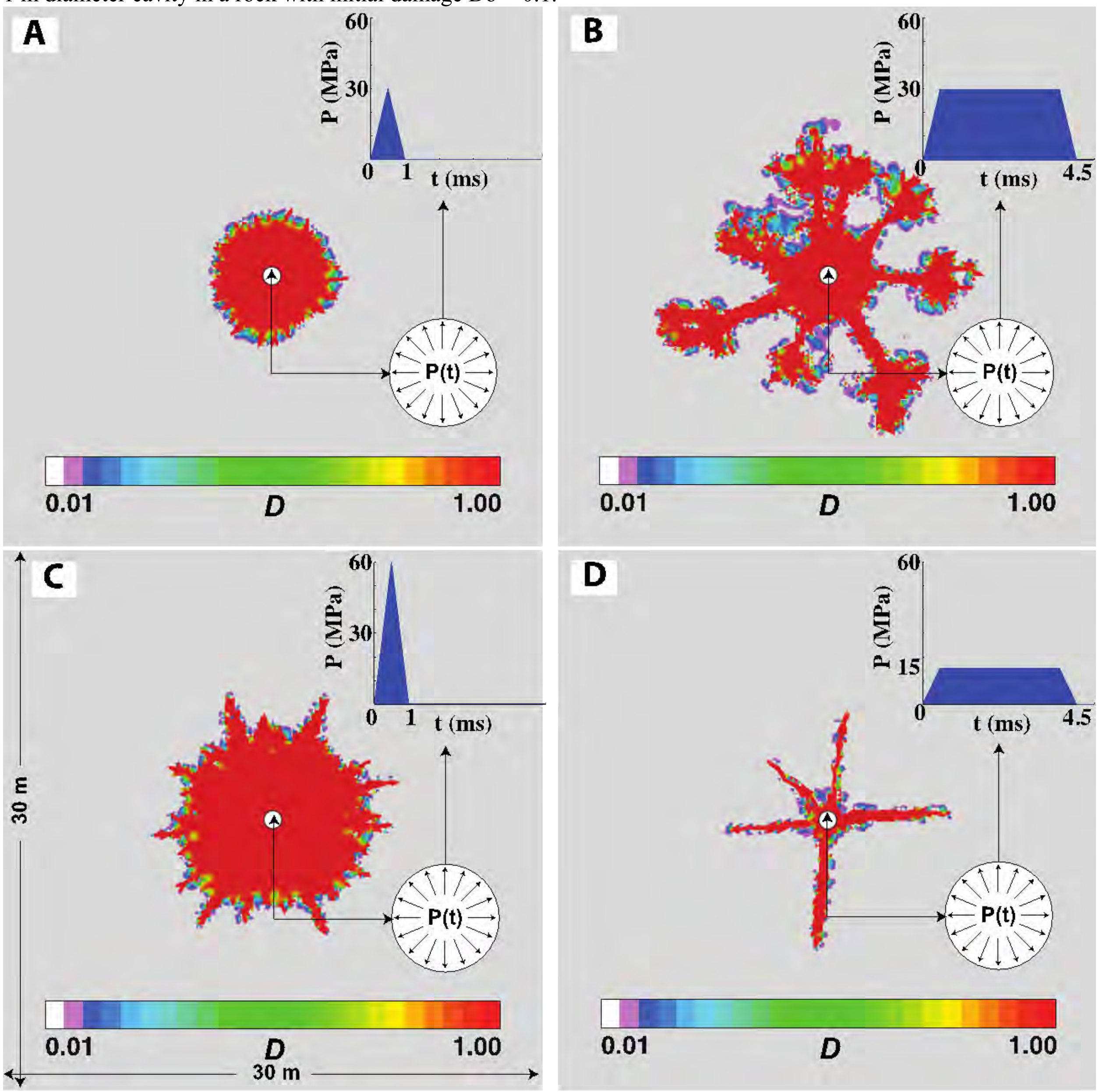

Figure 4. Damage created by different loading regimes.

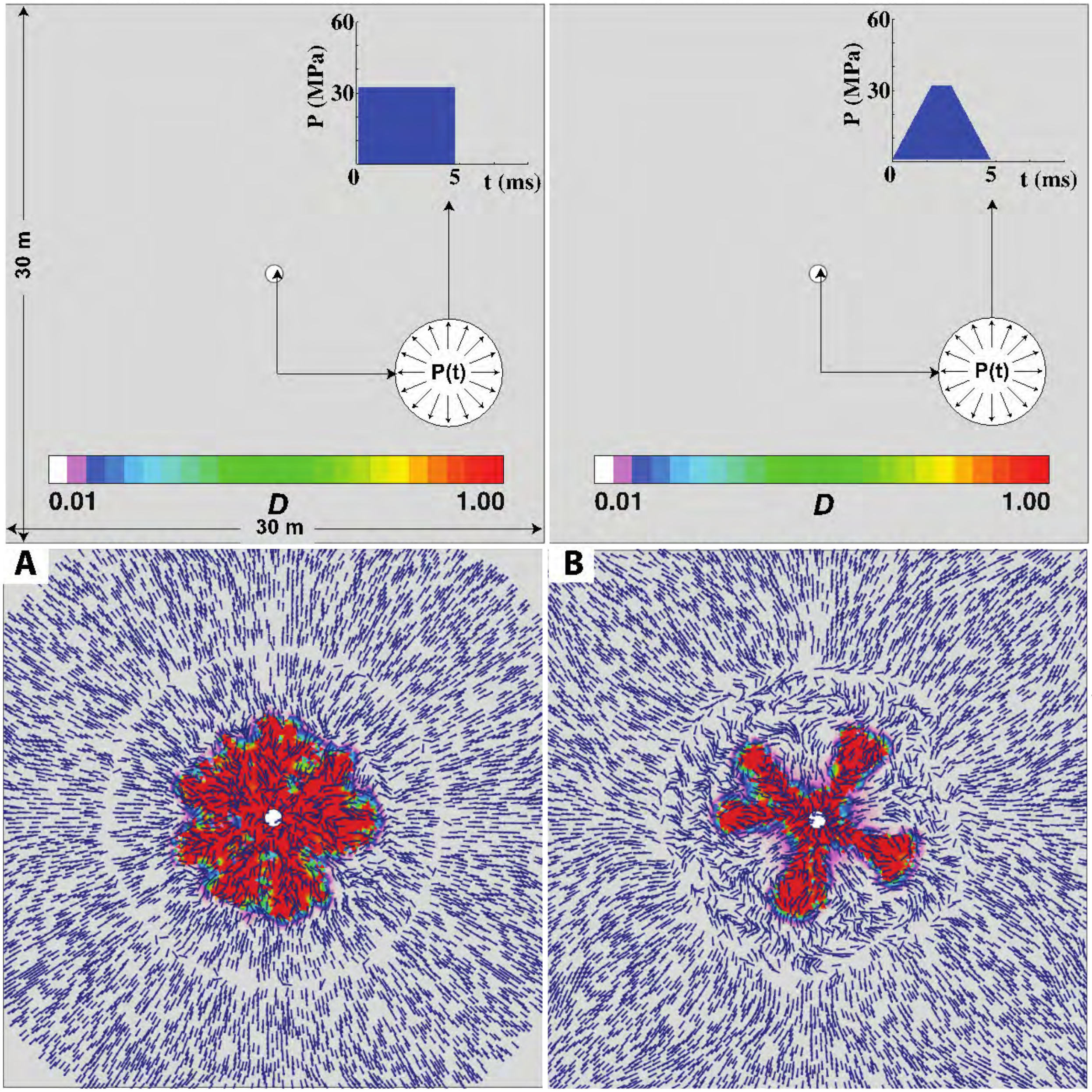

Figure 5. Comparison of displacement fields generated by a faster loading rate on the left and slower rate on the right. Note that the slower rate produces radial shear localizations which, in turn, produce S wave radiation.

CONCLUSIONS AND RECOMMENDATIONS

Our 2D explosion simulations demonstrate that the rise time of the explosion has little effect on the spatial extent of the damage. However, shorter rise times produce more radial fractures, which can be understood as a consequence of the higher strength close to the explosion. The duration of the pressure pulse has a large effect on the spatial extent of damage. Longer durations produce larger damage zones. The longer duration of the pressure pulse associated with slow-burn explosives may explain why they are observed to produce larger fracture zones.

Recommendations for future work include the following: 1) 3D calculations. The model is fully 3 dimensional, the only limitation is computation time. 2D simulations were run here to identify the important physical elements of the

problem. 2) Inclusion of a lithostatic pressure gradient. There is no difficulty in introducing a tectonic pre-stress and a lithostatic pressure gradient. 3) Investigation of the generation of P and S wave radiation. Since the ABAQUS code is dynamic, we can monitor the P and S waves generated by the explosion and the damage as demonstrated in Figure 5.

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